

ECCOMAS Thematic Conference

VIII International Conference on Computational Methods in Marine Engineering



# MARINE 2019

Göteborg, Sweden, 13-15 May 2019

IACM Special Interest Conference

## Procedure to Calibrate Composite Materials by Serial/Parallel Mixing Theory

Joel Jurado Granados

Invited Session: Lightweight Composite Materials in Shipbuilding

Göteborg, 13<sup>th</sup> May 2019

# SCIPEDIA

- **INTRODUCTION**
  - Composite materials on naval industry.
  - Analysis of composite structures and challenges.
- **FORMULATION: SERIAL/PARALLEL MIXING THEORY**
  - S/P Mixing Theory (S/P RoM) as a constitutive law manager.
- **CALIBRATION PROCEDURE**
  - Tests and methodology.
- **RESULTS & CONCLUSIONS**
  - Failure modes and load-position graphs.

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## INTRODUCTION. Use of composite materials on naval industry

SOLUTIONS ON NAVAL INDUSTRY ARE BECOMING MORE SPECIFIC, AS WELL AS THE MATERIALS USED TO DEAL WITH ARE BECOMING MORE COMPLEX.

COMPLEX SOLUTIONS REQUIRE SPECIFIC TOOLS

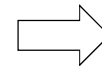
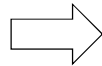
USE OF NUMERICAL MODELS

TO RESOLVE THE PERFORMANCE OF COMPLEX MATERIALS AND COMPLEX STRUCTURES

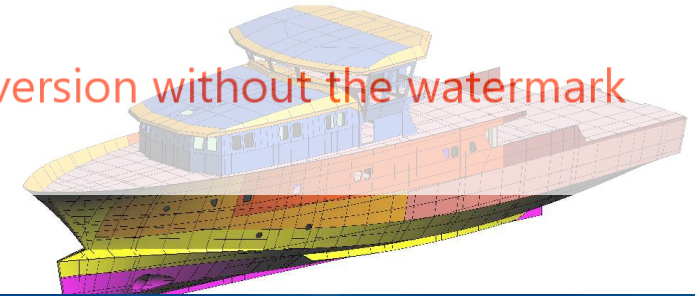
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### Limitations of usual models for composite materials

- Usually, composites are treated as orthotropic elastic materials.
- Failure analysis by means of failure criteria (maximum strain or stress, Tsai-Hill, Tsai-Wu,...).
- Ad hoc formulations require huge testing campaigns.
- Final collapse of the structure is hard to obtain by failure criteria.

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NO CHANCE TO OBTAIN POST-FAILURE PERFORMANCE NOR MATERIALS WITH COMPLEX MICRO-STRUCTURES

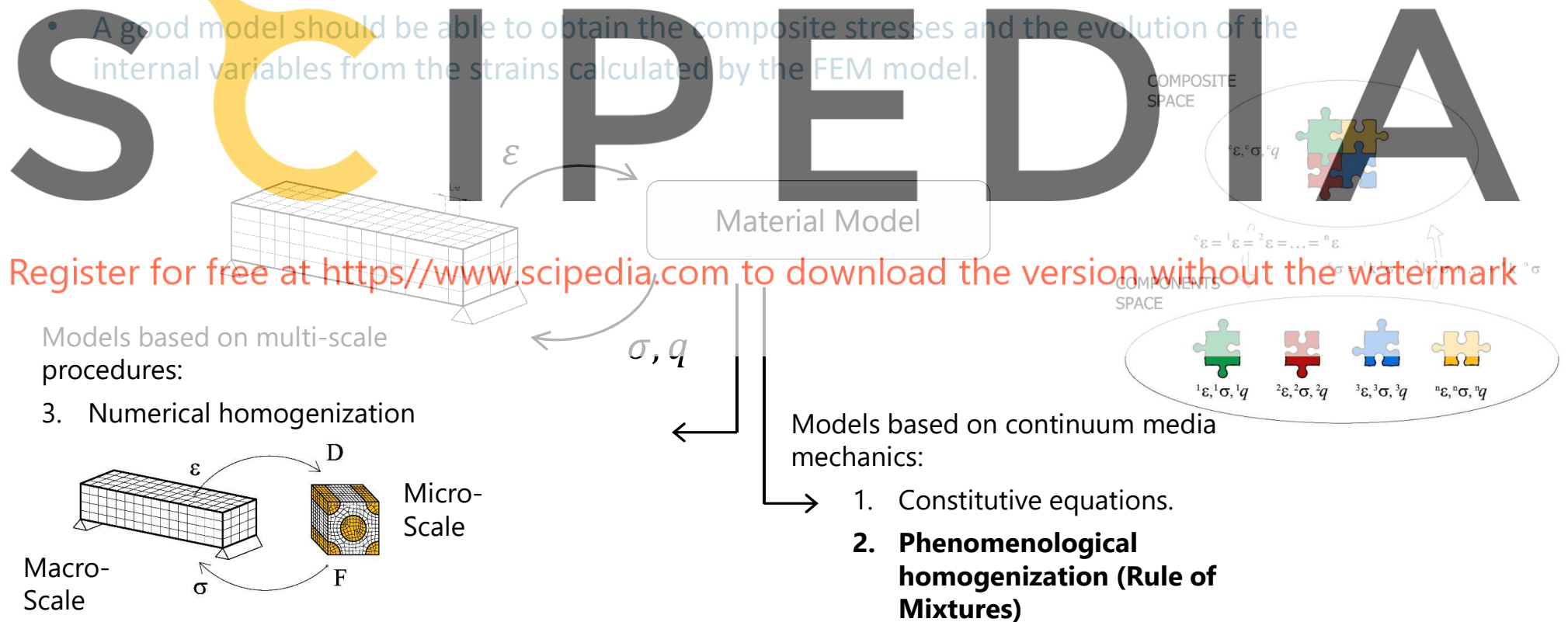
$$f_1(\sigma_1) + f_2(\sigma_2) + f_{11}(\sigma_1)^2 + f_{22}(\sigma_2)^2 + 2f_{12}(\sigma_1\sigma_2) + f_3(\tau_{12})^2 = 1$$

Elastic analysis:  
 $E_1, E_2, E_3, \nu_{12}, \nu_{23}, \nu_{31}$



One step beyond.

- A good model should be able to obtain the composite stresses and the evolution of the internal variables from the strains calculated by the FEM model.

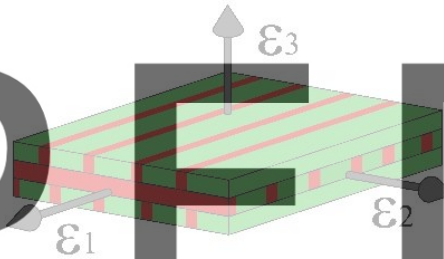


## INTRODUCTION. Challenges with composites

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### INTRODUCTION. Challenges with composites

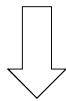
- Anisotropic behavior: material properties are orientation-dependent.
- Different failure modes (delamination, matrix cracking, fiber breakage,...)



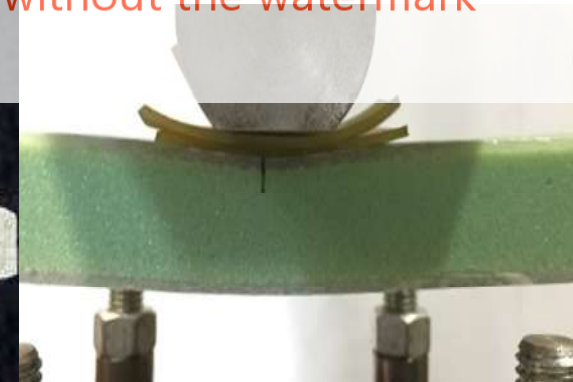
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- Lack of experimental data compared with other materials.

HOW TO DEAL WITH THESE CHALLENGES?



**Standardization of tests and calibration methods**



## SERIAL/PARALLEL MIXING THEORY. Hypothesis of RoM.

**Composites mechanical performance is obtained from components.**

**Hypothesis of RoM:**

- I) Each infinitesimal volumen of the composite contains a finite number of component materials.
- II) The contribution of each component is proportional to its volumetric participation.
- III) The volume of each component is minor than the composite volumen.

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- IV) Iso-strain condition on parallel direction (fiber direction).
- V) Iso-stress condition on directions different than fiber direction.

**Composite stress is obtained by solving each constitutive equation for each component (constitutive law manager).**

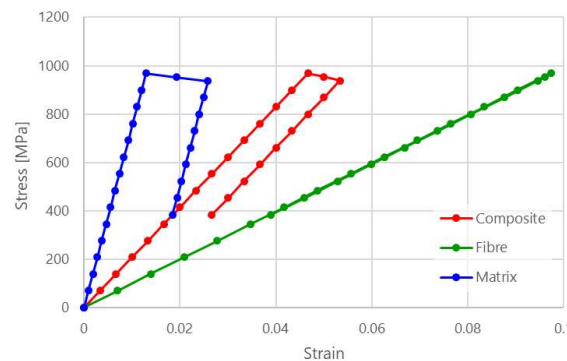
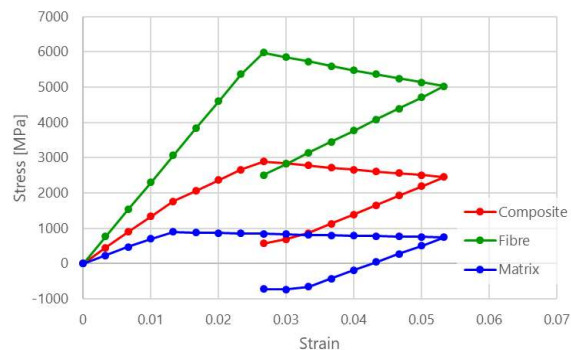
$$^c\sigma = \frac{\partial \Psi}{\partial \varepsilon} = \sum_{i=1}^n i_k \frac{\partial \Psi^i}{\partial \varepsilon^i} = \sum_{i=1}^n i_k \cdot i_{\sigma}$$

## SERIAL/PARALLEL MIXING THEORY

This formulation is a constitutive equations manager that provides the response of the composite by coupling the constitutive equations of its components.



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Serial behavior

$$\begin{cases} {}^c \epsilon_S = {}^m k^m \epsilon_S + {}^f k^f \epsilon_S \\ {}^c \sigma_S = {}^m \sigma_S = {}^f \sigma_S \end{cases}$$

Check for convergence:

$$[\Delta \sigma_S]^k = [{}^m \sigma_S]^k - [{}^f \sigma_S]^k \approx 0$$

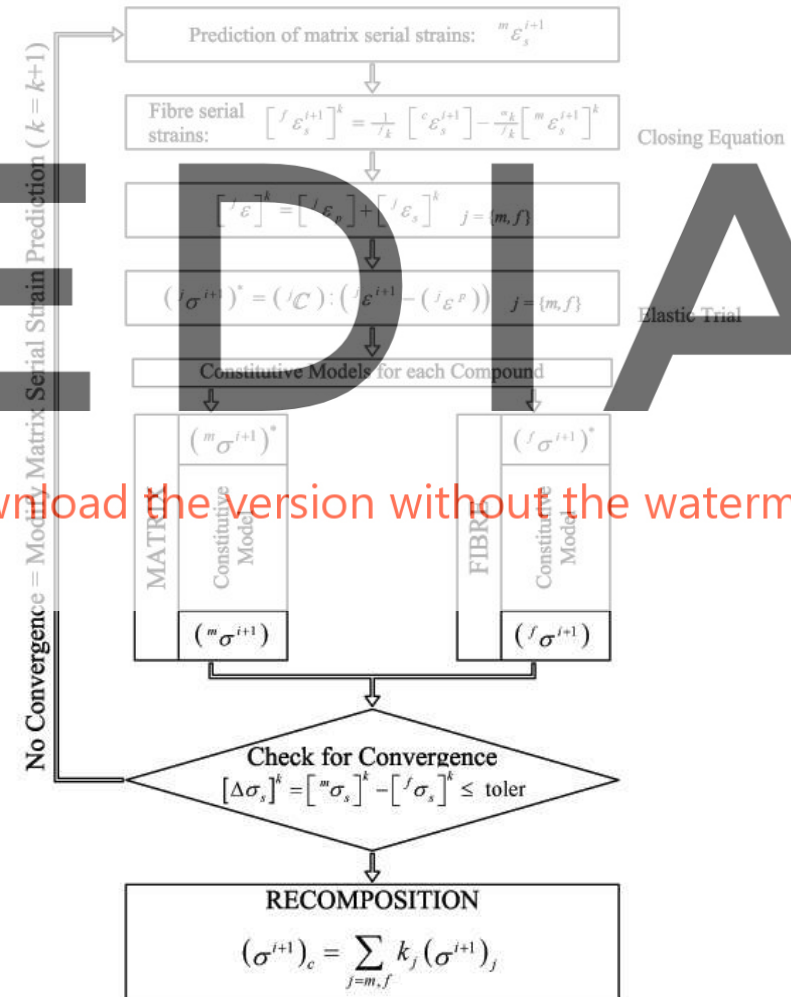


## SERIAL/PARALLEL MIXING THEORY

1. F.E. model gives composite strains.
2. Composite strains are decomposed on serial and parallel.
3. It is given a prediction of matrix serial strains  ${}^m\epsilon_s^{i+1}$ .
4. Then, matrix and fiber strain is obtained.
5. At this point, constitutive models for each component are applied, obtaining the stresses for the fiber and matrix.
6. Convergence is checked as:  

$$[\Delta\sigma_s] = [{}^m\sigma_s] - [{}^f\sigma_s] \leq \text{toler}$$
7. If no convergence is achieved, initial prediction of matrix strains is modified by an iterative process of Newton-Raphson.

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## SERIAL/PARALLEL MIXING THEORY

### ADVANTAGES OF USING S/P MIXING THEORY

- Any stacking sequence, no matter fiber orientation or fiber volume fraction.
- Formulation is able to couple different fiber/matrix systems, different constitutive laws.
- Non-linear performance of the composite can be defined from its constituents.

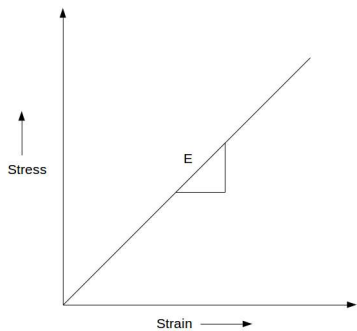
### HOW DO SP RoM WORKS AT COMPOSITE LEVEL?

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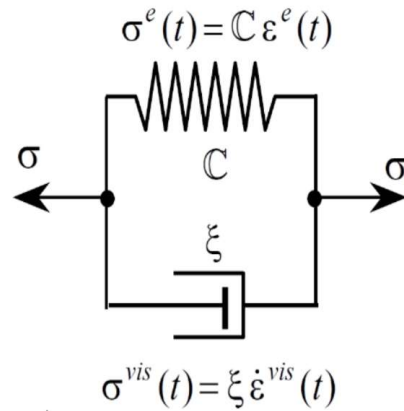
- SP RoM is applied inside each ply.  $\varepsilon_i = \sigma_i$
- Stress on the whole composite is obtained applying classic RoM.  ${}^c\sigma = \sum_{i=1}^n ({}^i k {}^i \sigma)$

## S/P MIXING THEORY. Constitutive laws for materials.

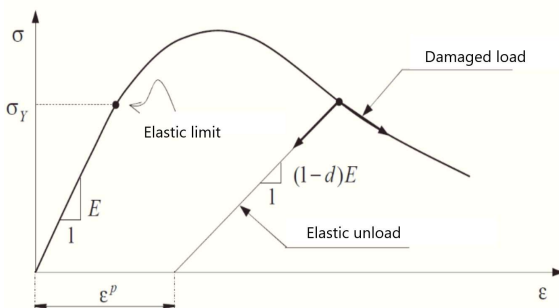
### Elastic law



### Visco-plastic law



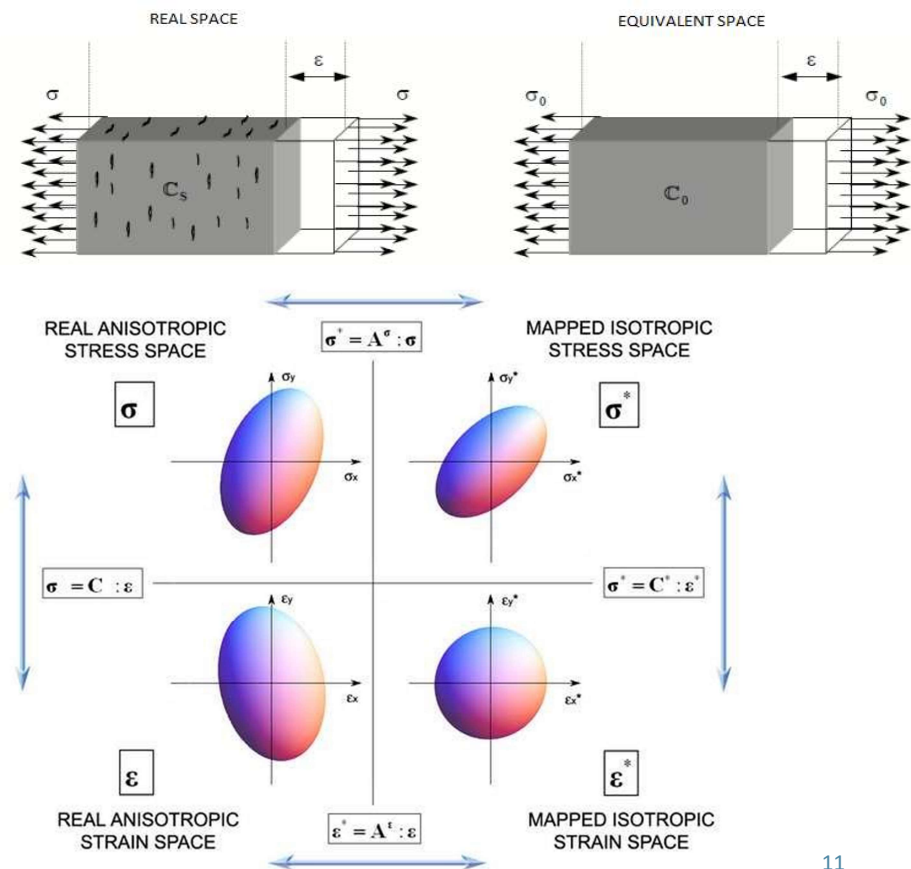
### Damage-plastic law



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### Damage law

$$\sigma = (1 - d) \cdot \sigma_0 \rightarrow \mathbb{C}_S : \varepsilon = (1 - d) \cdot \mathbb{C}_0 : \varepsilon$$



## EXPERIMENTAL CAMPAIGN

- Two systems were selected: LEO System and Sicomin system.
  - LEO System: Vinylester matrix reinforced with fiber glass.
  - Sicomin System: Epoxy matrix reinforced with fiber glass.

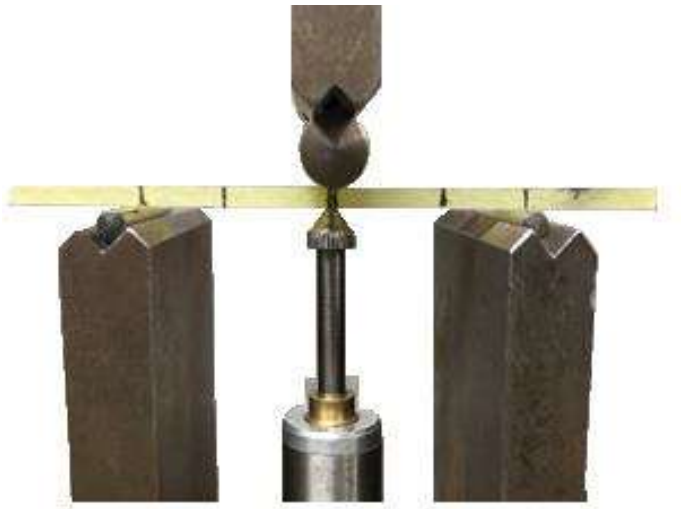
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### 3-POINT BENDING TEST (3PB)

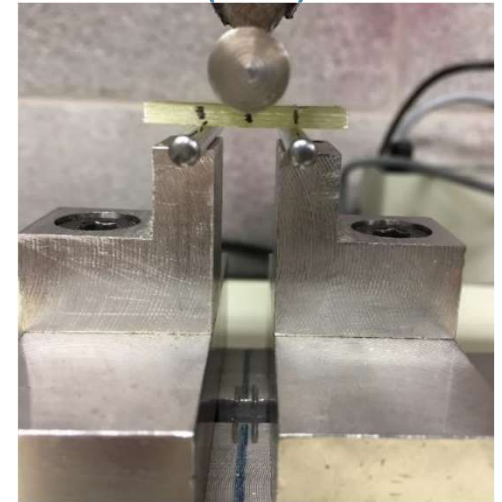


### TENSILE TEST



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### SHORT BEAM SHEAR TEST (SBS)



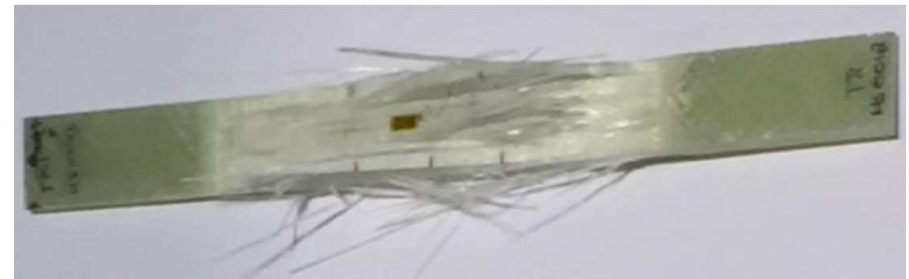
## CALIBRATION PROCEDURE

### WHICH PARAMETERS ARE REQUIRED?

- **Composite architecture** → Fiber/Matrix system, ply orientations, participation of each ply on the whole laminate.
- **Elastic properties of the constituents and non-linear properties of the constituents (fiber and matrix)**  
(SP RoM AS A CONSTITUTIVE LAW MANAGER!)
- **We have proposed a procedure for material calibration. An experimental campaign have been conducted to characterize FibreShip materials.**

### HOW DO WE OBTAIN CONSTITUENT PARAMETERS FROM LAMINATE TESTING?

- Longitudinal UD is fibre-driven (parallel behavior).
  - **Fibre parameters from longitudinal tests.**
- Transverse UD shear performance are matrix-driven (serial behavior).
  - **Matrix parameters from transverse and shear tests.**
- **Reverse engineering** → We know how SP RoM works.



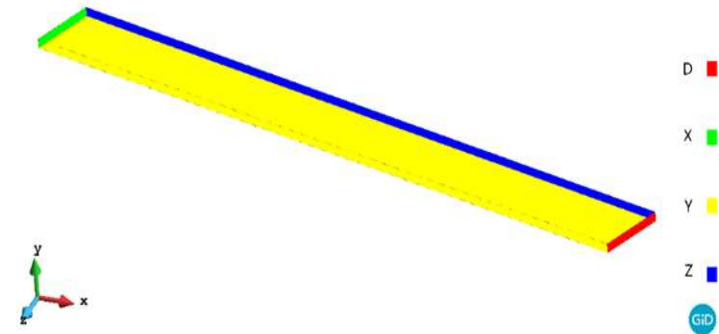
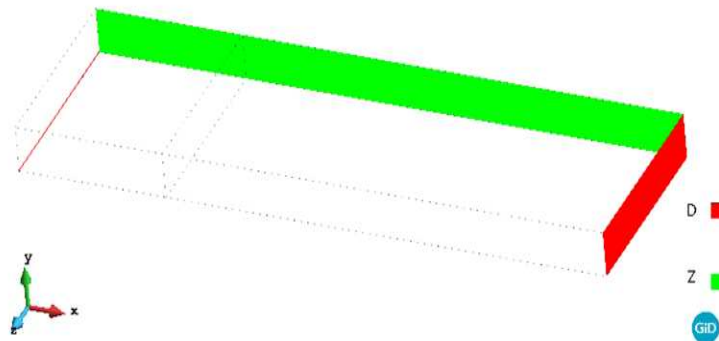


## CALIBRATION PROCEDURE

Parameter	Method to obtain
FIBRE ORIENTATION	DEFINED BY DESIGN
FIBRE AND PLY VOLUME PARTICIPATION	BURN OFF TEST. VERIFIED BY LONGITUDINAL AND TRASNSVERSE TENSILE TESTS
FIBRE YOUNG MODULUS	DATASHEET PRODUCT. VERIFIED BY LONGITUDINAL TENSILE TESTS
MATRIX YOUNG MODULUS	DATASHEET PRODUCT. VERIFIED BY TRANSVERSE TENSILE TESTS
POISSON COEFFICIENT	LITERATURE
SHEAR MODULUS	SHORT BEAM SHEAR TEST (SBS).
FIBRE TENSILE STRENGTH	LONGITUDINAL TENSILE TEST.
FIBRE COMPRESSIVE STRENGTH	LONGITUDINAL 3 POINT BENDING TEST (3PB).
MATRIX TENSILE STRENGTH	TRANSVERSE TENSILE STRENGTH
MATRIX COMPRESSIVE STRENGTH	TRANSVERSE 3PB TEST.
MATRIX SHEAR STRENGTH	SBS TEST.
FIBRE FRACTURE ENERGY	LONGITUDINAL TENSILE TEST
MATRIX FRACTURE ENERGY	SBS TEST.

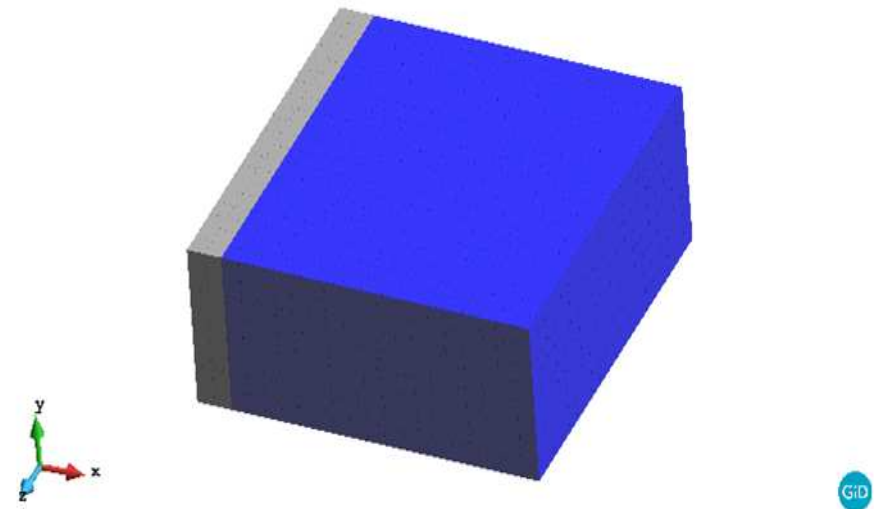
## MODELS GEOMETRY

3PB BC



Tensile test model

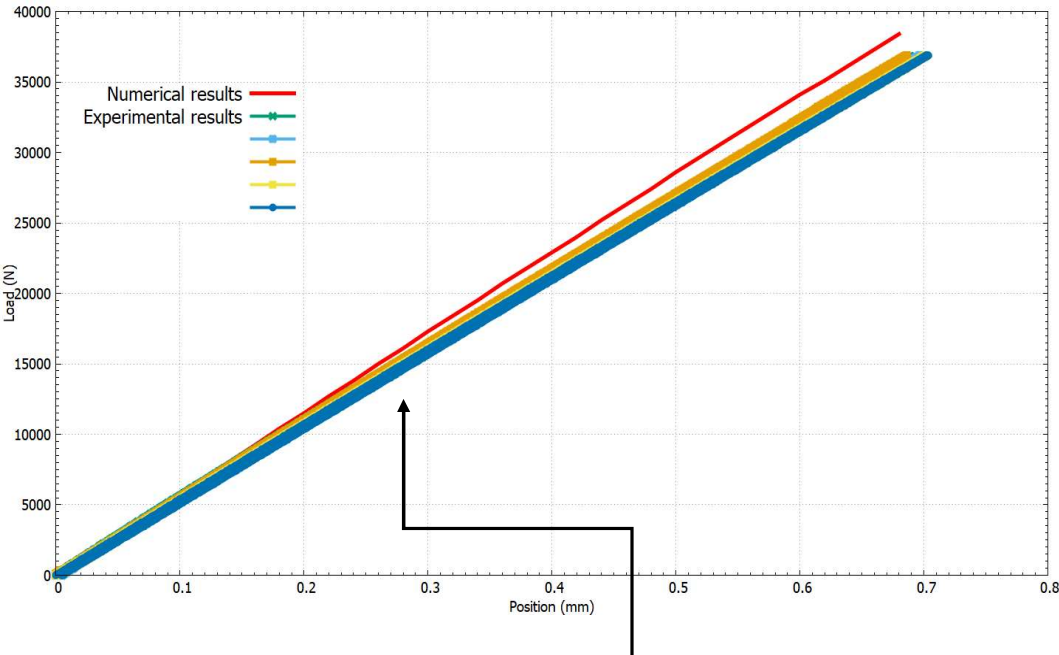
Test	Elements nº	Nodes nº	Element type	Dimensions
Tensile	20.250	28.184	Linear hexahedral	135 x 12.5 x 1.5 mm
Flexure	10.000	12.636	Linear hexahedral	40 x 12.5 x 3 mm
Shear	3.200	3.969	Linear hexahedral	7.5 x 7.5 x 3 mm



Shear test model

## RESULTS. Load-position curves

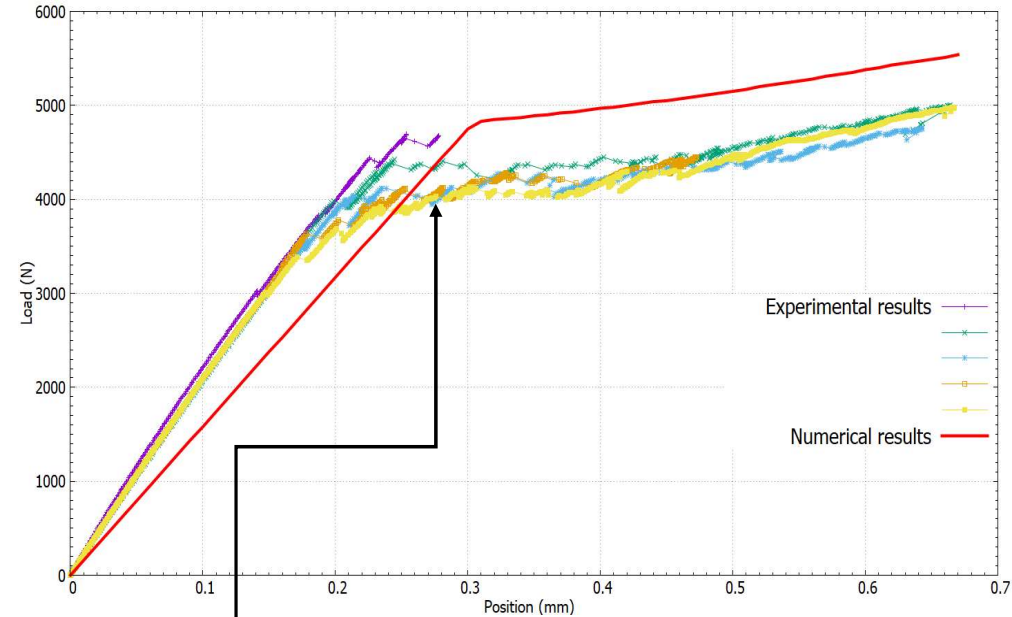
### LONGITUDINAL TENSILE TEST



Stiffness of the laminate is obtained

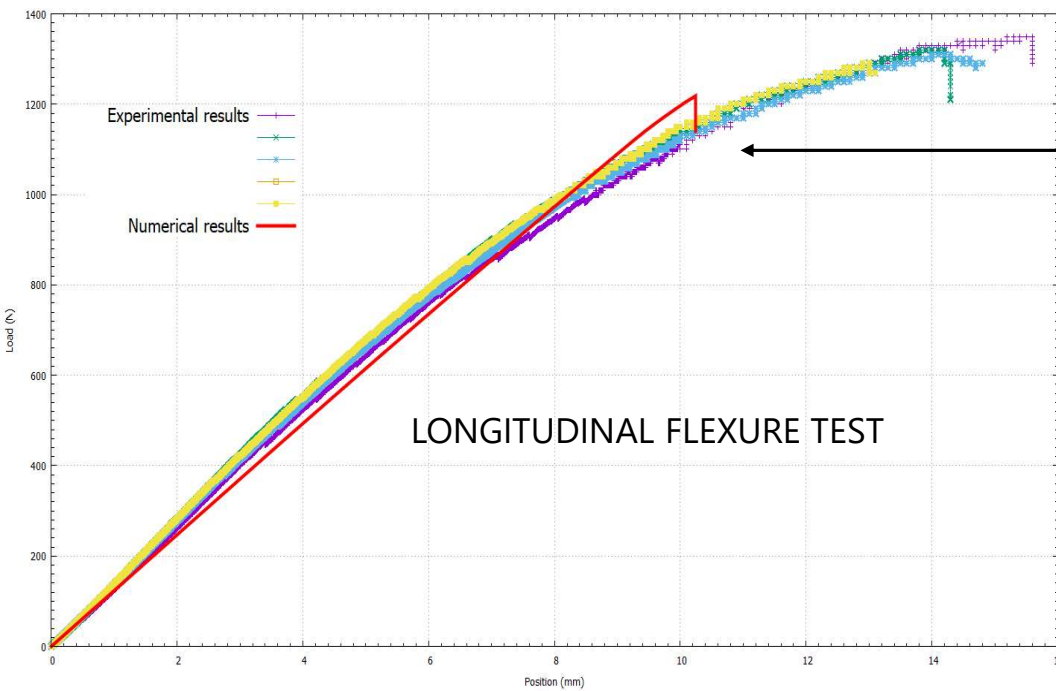
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### TRANSVERSE TENSILE TEST

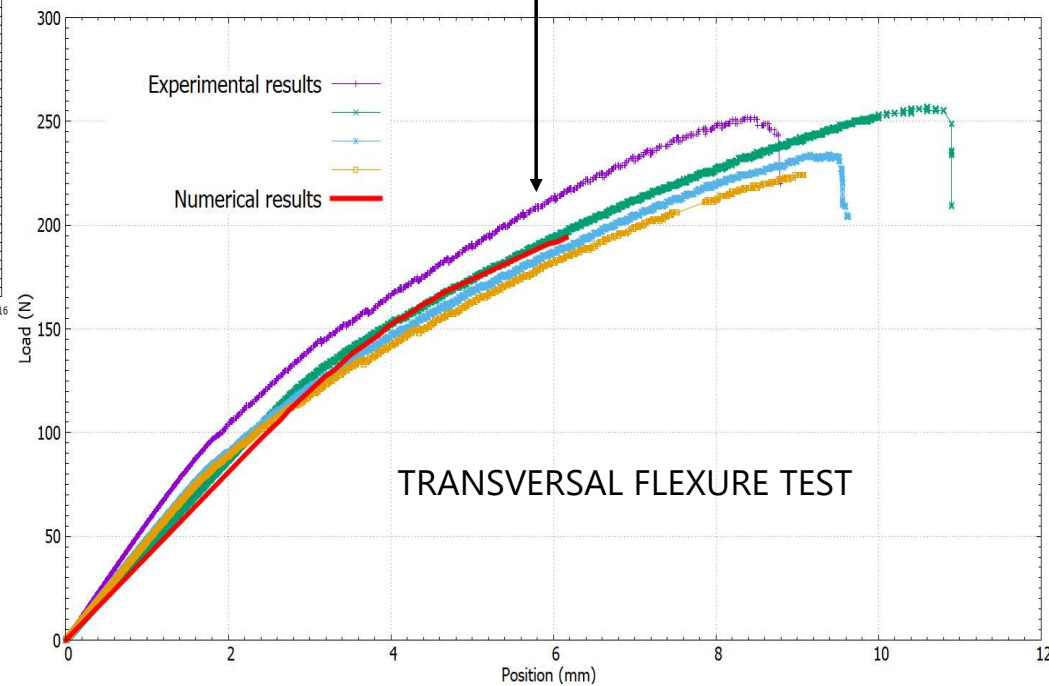


Once matrix fails, only appear the stiffness of transverse (now longitudinal) fibres.

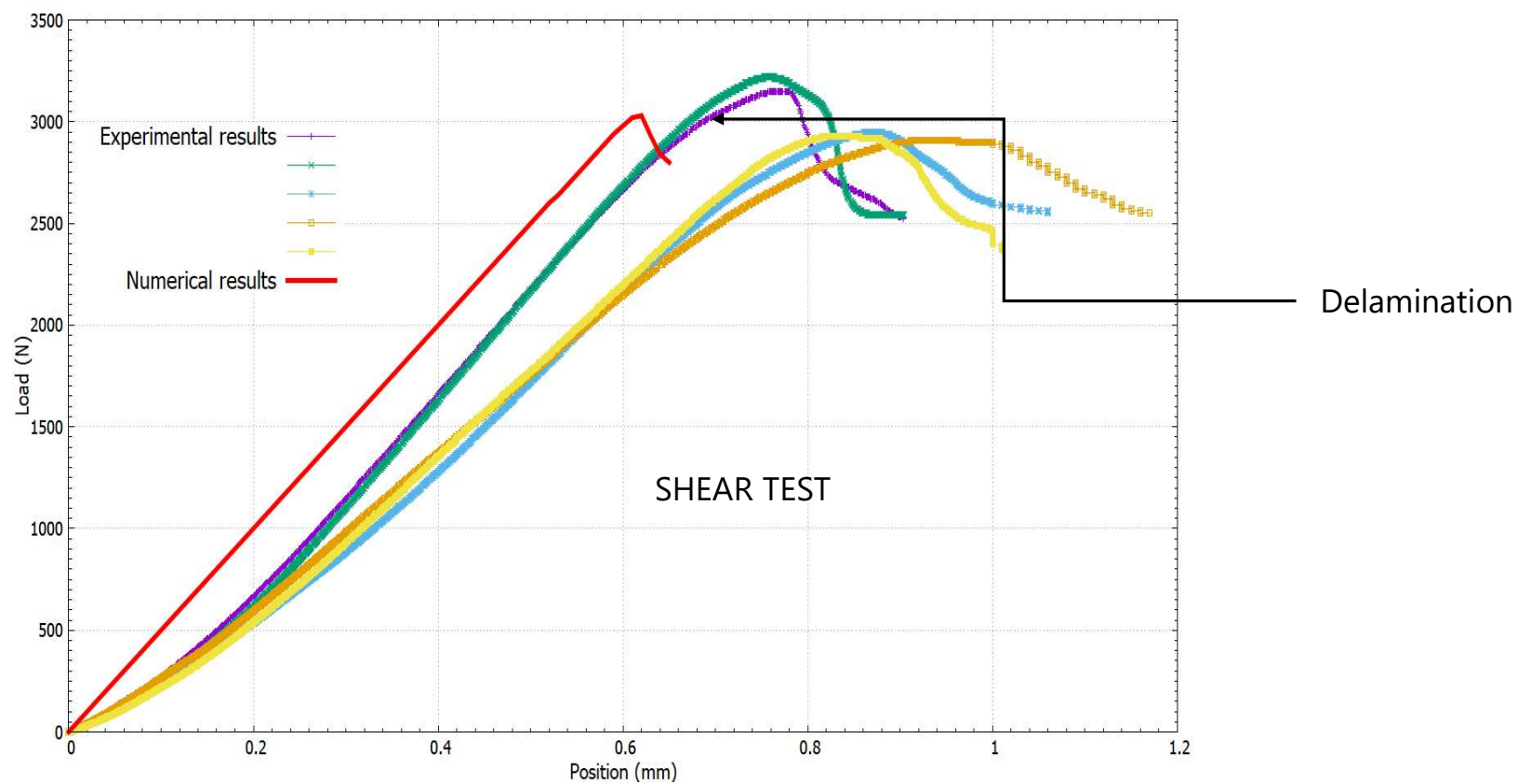
## RESULTS. Load-position curves



Stiffness obtained, but not failure load  
(still conservative).

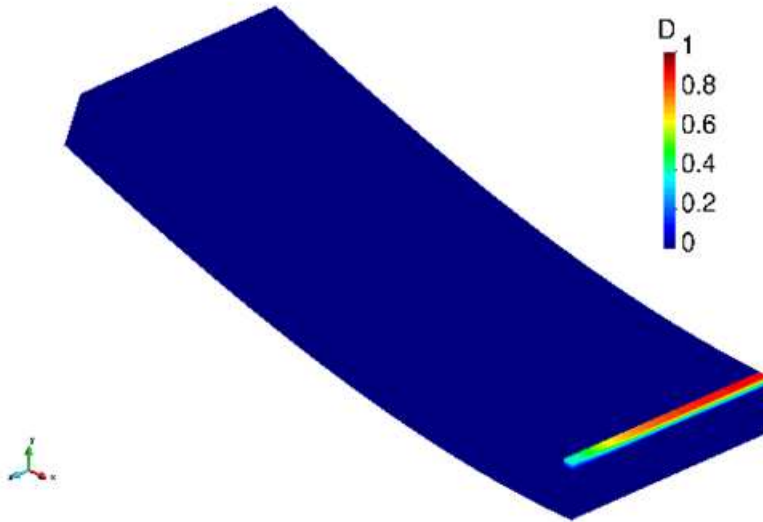


## RESULTS. Load-position curves





## RESULTS FEM MODELS. Failure modes

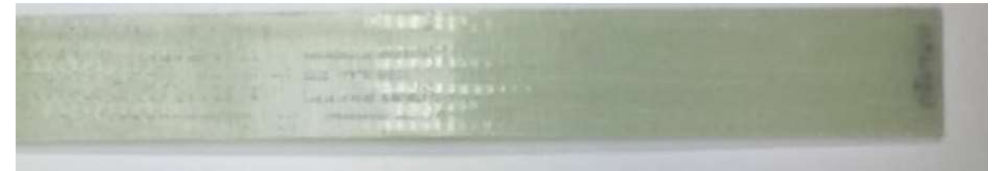
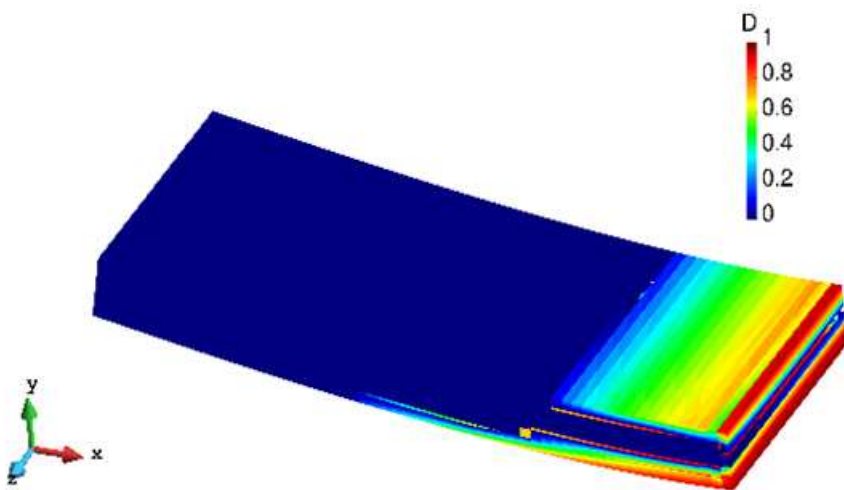


FIBER DAMAGE FOR LONGITUDINAL FLEXURE TEST



## RESULTS FEM MODELS. Failure modes

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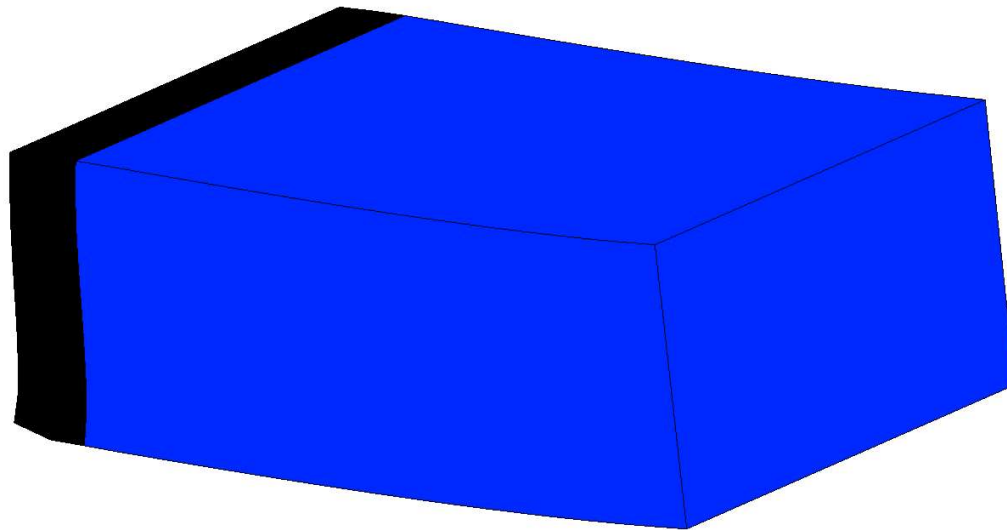


DAMAGE FOR TRANSVERSAL FLEXURE TEST

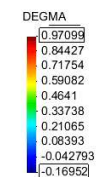


## RESULTS FEM MODELS. Failure modes

### MATRIX DAMAGE FOR SHEAR TEST



MECHANICAL, step 0.205  
Contour Fill of Int.Var://Composite2 //Layer01 //mn//DEGMA  
Deformation ( x3): DISPLACEMENTS of DISPLACEMENTS, step 0.205.

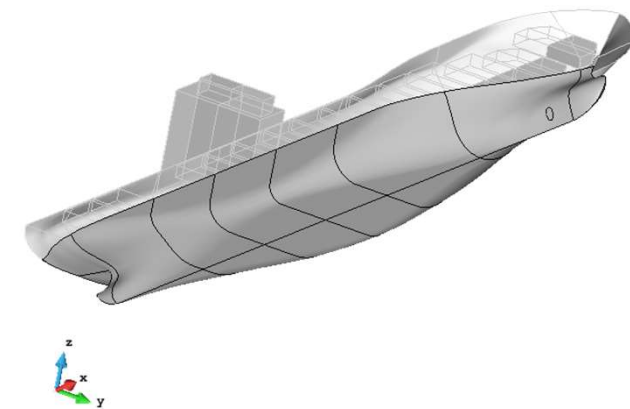
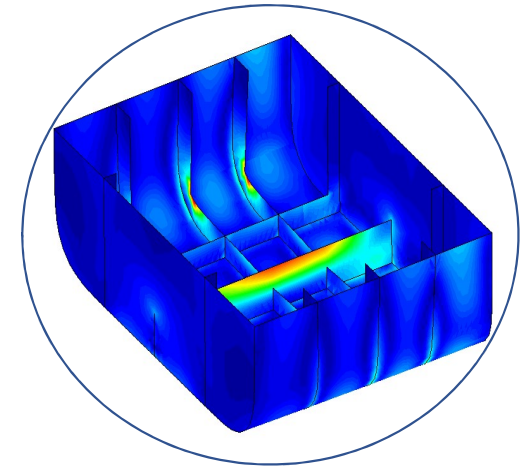


## CONCLUSIONS

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### RELEVANT ASPECTS

- Composite performance is obtained by means of fiber and matrix behavior, regardless fiber orientation or fiber participation, what reduces number of tests to be done.
- A procedure to calibrate the S/P Mixing Theory is built.
- Failure modes of the composite can be obtained.
- S/P Mixing Theory is compatible with known failure criteria (Tsai-Hill, first ply failure, etc).



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ACKNOWLEDGEMENTS. This work has been supported by the European Union's Horizon 2020 research and innovation program under grant agreement No. 723360 (Fibreship project)

**THANK YOU**



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